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Warm and Cold Molecular Gas in Luminous Infrared Galaxies

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Abstract. We present the properties of the warm and cold molecular gas in a sample of local Luminous Infrared Galaxies in the Great Observatories All-sky LIRG Survey (GOALS). The rotational transitions of H_2 observed in the Mid-Infrared Spectra from the Spitzer Survey trace gas at temperatures about 100K, while the 12 CO (1-0) maps acquired with the Combined Array for Millimeter Astronomy identify the morphology of the cold (less than 40K). The 17.1 μm S(1) transitions of warm H_2 is detected in 94% of the 247 LIRG nuclei analyzed. The warm H_2 S(0) to S(3) emission is correlated with the 6.2 μm and the [Si II] cooling line. This suggests that the H_2 is mostly excited in PDR. The large scatter in correlation both for merging and non-merging sources suggests that some of the excitation appear to be due to shocks associated with SNe. This is consistent with the high fractions of [FeII]/[OIV] $\geq$ 1 we measure in about 20% of the sources and the number of sources with detected S(7) emission. The larger scatter in the PAH to H_2 may also be due to both the presence of an AGN hard ionizing continuum and the the large range of interactions observed in LIRGs (about 50% of LIRGs in GOALs are interacting) . The 16 12CO(1-0) maps for LIRGs in a merger sequence show that molecular gas surface densities range between about 65 $M_\odot/pc^2$ to 2600 $M_\odot/pc^2$ with a median and mean value of 290 and 571 $M_\odot/pc^2$ respectively. This suggests that LIRGs have a wide range of molecular gas surfaces but in general a factor of a few greater than normal galaxies and not the extreme values seen typically in Ultraluminous Infrared Galaxies (ULIRGs) or PG QSOs. We find that molecular gas depletion times increase with merger stage but do not appear to vary with stellar mass.

1. Introduction

Luminous Infrared Galaxies (LIRGs) (LIR[8-1000 μm] $\geq 10^{11} L_\odot$ provide the missing link between the extreme objects we see at high redshift and $L^\star$ galaxies. Evidence from this comes from the discovery of a significant population of faint, far-IR/submm sources with the new generation of submm arrays (Hughes et al. 1998, Barger et al. 1998).

The Great Observatories All-sky LIRG Survey (GOALS) targets a complete sample of two hundred and three Luminous Infrared Galaxies (LIRGs; L) in the local Universe selected from the IRAS Revised Bright Galaxy Sample (Armus et al. 2009). GOALS brings together HST, Spitzer Space Telescope (imaging and spectroscopy), GALEX, Chandra X-ray Observatory, NIR and ground-based optical spectroscopic data to understand low-z ($\leq$0.088) LIRGs. Here we present an investigation of the properties of warm molecular hydrogen from measurements of the rotational transitions emitted in the mid infrared range between 5 and 30 μm for the entire sample of LIRGs. In addition we have acquired 12CO(1-0) 2ërësolution maps with the Combined Array for

Millimeter Astronomy. Molecular hydrogen provides the main source of fuel for both star-formation and the growth of supermassive black holes.

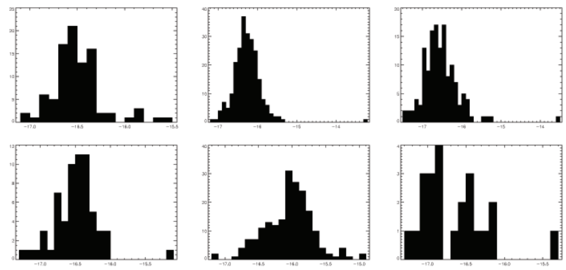

Figure 1. Histograms of measured fluxes for the H_2 molecular gas corresponding to the following rotational transitions, S(0) J=2-0, S(1) J=3-1, S(2) J=4-2, S(3) J=5-3, S(5) J=7-5 and S(7) J=9-7. The fluxes are given in log[W/m^{-2}]

1.1. Merger classification and AGN fraction

The GOALS sources were classified in 5 stages: (0) no obvious sign of a disturbance either in the IRAC or HST morphologies, or published evidence that the gas is not in dynamical equilibrium (i.e. undisturbed circular orbits), (1) early stage, where the galaxies are within one arc minute of each other, but little or no morphological disturbance can be observed; (2) the galaxies exhibit bridges, and tidal tails, but they do not have a common envelope and each optical disk is relatively intact; (3) the optical disks are completely destroyed but two nuclei can be distinguished; (4) the two interacting nuclei are merged. The classification scheme was based on a combination of HST, IRAC 3.6, and DSS images. A search in the literature for detailed dynamical analysis based on HI data such as those in Yun et al. (2004) was also done. For the few sources with published HI interferometric data, the merger class was determined on the basis of that data .

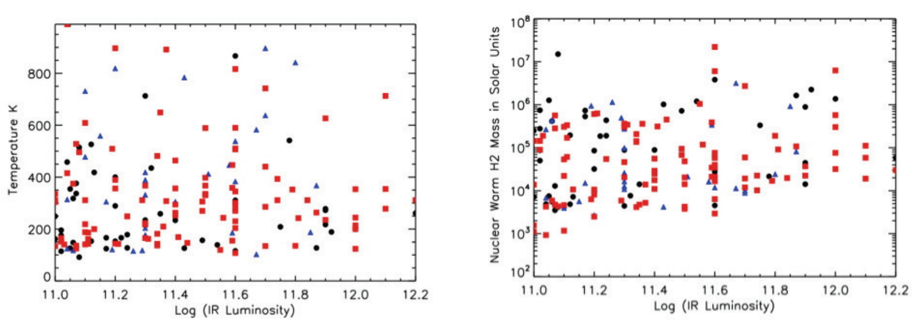

Figure 2. Left: Temperature and Mass Right: of H_2 gas versus IR luminosity, circles are non-mergers, triangles are early mergers, and squares are advanced mergers. Note that for some objects the excitation diagram suggests that more one temperature component is necessary to fit the observed emission. As such one objects could be represented by several points on this a plot.

The AGN contribution to the MIR emission was estimated in Petric et al. 2011 by employing several diagnostics based on the properties of the [NeV], [OIV] and [NeII] fine structure gas emission lines, the 6.2 μm PAH equivalent width (EQW) as well as the shape of the MIR continuum. When summing up the total IR luminosity contributed by AGN in all the LIRGs in our sample, we find that AGN contribute approximately 12% to the total energy emitted by LIRGs in the local universe. By separating the GOALS sources according to merger stage Petric et al. 2011 found that there is a significant increase in the fraction of AGN dominated sources among those galaxies in the latest stages of interaction. This trend is driven by the ULIRGs in the sample, since these objects tend to be late stage mergers and have larger AGN fractions than the LIRGs . This is consistent with findings of previous authors using optical diagnostics for LIRGs, MIR studies of ULIRGs and PG QSOs and with models which predict that mergers of gas-rich spirals fuel both star-formation and accretion onto a super-massive black hole.

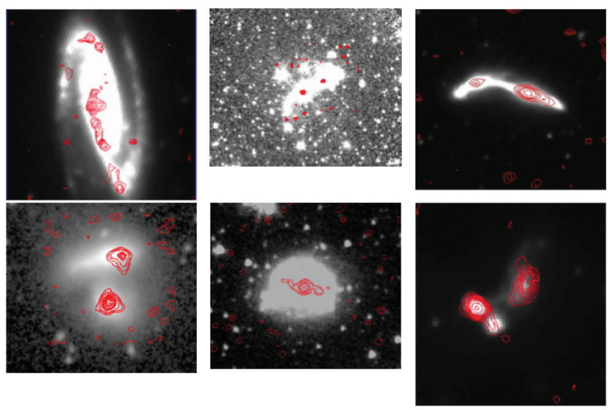

Figure 3. Velocity Integrated12CO(1-0) intensity for NGC 0958, VV 250, NGC 6670, IIZw 96, UGC 2369 and UGC 2608, two sigma rms contours of 12 CO(1-0) emission are atop IRAC 3.6 μm images.

2. Warm Molecular Gas

Figure 1 shows histograms for S(0) through S(7) detections. No S(4), S(6) lines were detected. We detect the S(0) line in 40% of our sources, in great contrast with the Higdon et al. 2009 study of ULIGs at similar sensitivities. The brightest line, the S(1) line at 17μm is detected in 94% of sources and the summed S(0) through S(3) emission scales with the total flux in the 6.2 μm PAH line, but with a large scatter as well as with the total [SiII] emission.

We derive excitation diagrams from which we estimate masses and temperature. Figures 2a and 2b show that there are no tight relations between the warm molecular gas mass and temperature and the IR luminosities or merger stages of the LIRGs. However, the S(7) line is detected predominantly in merging systems suggesting that, suggesting that the merger does tend to produce hotter molecular gas components ($\geq$ 600K) probably through shocks associated with the tidal interactions. A Spearman rank correlation

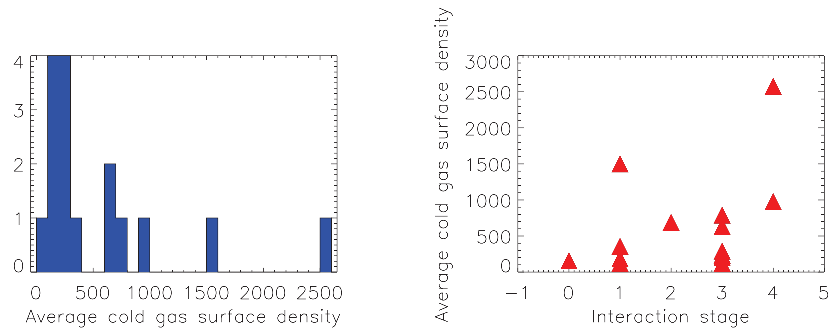

Figure 4. Top: Velocity Integrated12CO(1-0) intensity for NGC 0958, VV 250, NGC 6670, IIZw 96, UGC 2369 and UGC 2608, two sigma rms contours of 12 CO(1-0) emission are atop IRAC 3.6 μm images. Bottom Left: Histogram of the molecular gas surface densities which range between about 65 $M_\odot/pc^2$ to 2600 $M_\odot/pc^2$ with a median and mean value of 290 and 571 $M_\odot/pc^2$ respectively. Bottom right: Average molecular gas surface density as a function of interaction stage as described in section 2.1

tests also suggest that the H_2 masses are correlated with the IR luminosity but with a significance level of only

3. Cold Molecular Gas

Cold molecular gas is the primary source of fuel for both accretion and star-formation activity. The current paradigm put forward by (e.g. Sanders et al. 1988, Scoville & Norman 1988, Di Matteo et al. 2007), is that gas in merging galaxies is driven to the center feeding both a central supermassive black hole and inducing star formation. Here we test how the gas surface density and the associated molecular gas depletion time change with interaction stage.

We observed 16 galaxies with the CARMA interferometer and are sensitive to $10^7 M(\odot)$. Figure 2 shows six examples how the 12 CO(1-0) compares with the IRAC 3.6 μm images. We measure surface densities that range between about 65 $M_\odot/pc^2$ to 2600 $M_\odot/pc^2$ with a median and mean value of 290 and 571 $M_\odot/pc^2$ respectively. This suggests that LIRGs have a wide range of molecular gas surfaces but in general a factor of a few greater than normal galaxies and not the extreme values seen typically in Ultraluminous Infrared Galaxies (ULIRGs) or PG QSOs.

We estimate the gas depletion times by using the star-formation rates from (Howell et al. 2010) which were measured using both UV data from GALEX and IR data from SPITZER MIPS. We find that molecular gas depletion times increase with merger stage but do not appear to vary with stellar mass. The stellar masses where also obtained from Howell et al. (2010).

References

Armus et al. 2009, PASP, 121, 559
Di Matteo, P., Combes, F., Melchior, A,, Semelin, B., 2007, A&A, 468, 61
Howell et al. 2010, ApJ, 715, 572H
Petric, A. et al. 2011, ApJ, 730, 28

Roussel, H. et al. 2007, ApJ, 669, 959
Higdon, S et al. 2006, ApJ, 2006, 648, 323
Sanders, D., Scoville, N., Soifer, B., 1988, ApJ, 335, 1
Scoville, N. et al. 1989, ApJ, 345, 25